



University
of Glasgow

HIGH FREQUENCY COMMUNICATION SYSTEMS

Lecture 9

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Spring 2022

- Array Directivity
- Planar Antenna Arrays
- Feeding Networks
- Software-defined Radio

WHAT IS IT?



Figure 1: Guess what the picture is showing.

DIRECTIVITY

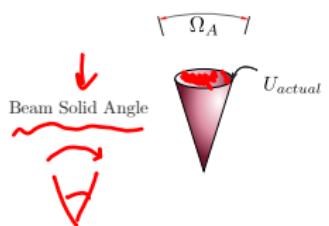
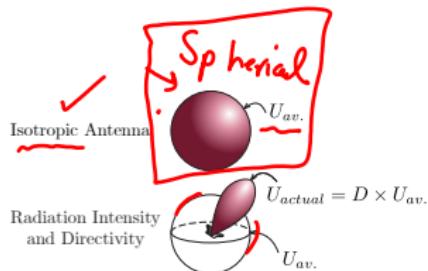
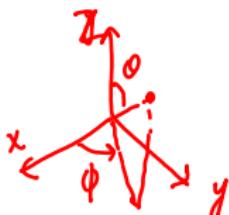
ANTENNA ARRAY DIRECTIVITY

- Recall *directivity* describes the antenna radiation in a given direction
- We use the *radiation intensity* $[U(\theta, \phi) = 1/2 \operatorname{Re}(\vec{\mathbf{E}} \times \vec{\mathbf{H}}^*) \cdot \hat{\mathbf{r}}]$ to assess the power radiated in a given direction per unit solid angle
- We define the directivity as:

$$D = \frac{4\pi}{\Omega_A}$$

where, $\underline{\Omega_A} = \iint |EF(\theta, \phi)|^2 |AF(\theta, \phi)|^2 d\Omega$

$$[d\Omega = \sin \theta d\theta d\phi]$$



FINDING THE BEAM SOLID ANGLE

Let us consider a uniformly excited, uniformly spaced linear array where all the elements are *isotropic* ($EF = 1$). From the previous lecture, we got:

$$N \quad |AF|^2 = \left| \frac{\sin N\psi/2}{N \sin \psi/2} \right|^2 \equiv \frac{1}{N} + \frac{1}{N^2} \sum_{m=1}^{N-1} (N-m) \cos m\psi \quad (1)$$

Knowing,

$$\boxed{\checkmark \psi = kd \cos \theta + \alpha} \xrightarrow{\text{spacing}} \sin \theta d\theta = -\frac{1}{kd} d\psi \quad \xrightarrow{\text{phase}}$$



The beam solid angle Ω_A then becomes:

Sphere

$$\begin{aligned} \Omega_A &= \int_0^{2\pi} d\phi \int_0^\pi |AF(\theta)|^2 d\theta = 2\pi \int_{kd+\alpha}^{-kd+\alpha} |AF(\psi)|^2 \left(\frac{-1}{kd} \right) d\psi \\ &= \frac{2\pi}{kd} \int_{-kd+\alpha}^{kd+\alpha} |AF(\psi)|^2 d\psi \end{aligned} \quad (2)$$

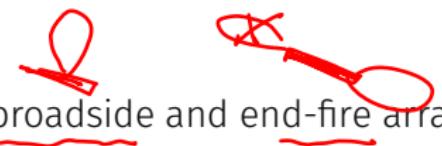
Solving (1) and (2) we get:

$$\begin{aligned}
 \Omega_A &= \frac{2\pi}{kd} \left[\frac{1}{N} \int_{-kd+\alpha}^{kd+\alpha} d\psi + \frac{2}{N^2} \sum_{m=1}^{N-1} (N-m) \int_{-kd+\alpha}^{kd+\alpha} \cos m\psi d\psi \right] \\
 &= \frac{2\pi}{kd} \left[\frac{1}{N} \psi \Big|_{-kd+\alpha}^{kd+\alpha} + \frac{2}{N^2} \sum_{m=1}^{N-1} (N-m) \frac{\sin m\psi}{m} \Big|_{-kd+\alpha}^{kd+\alpha} \right] \\
 &= \frac{2\pi}{kd} \left[\frac{1}{N} (2kd) + \frac{2}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{m} [\sin m(kd+\alpha) - \sin m(-kd+\alpha)] \right]
 \end{aligned}$$

Using the trigonometric identity, $\sin(a+b) = \sin a \cos b + \cos a \sin b$, we get:

$$\boxed{\Omega_A = \frac{4\pi}{N} + \frac{4\pi}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{mkd} 2 \cos m\alpha \sin m kd}$$

DIRECTIVITY EXPRESSIONS



The directivity for the broadside and end-fire arrays is thus:

$$D = \frac{4\pi}{\Omega_A} = \frac{1}{\frac{1}{N} + \frac{1}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{mkd} 2 \cos m\alpha \sin mkd}$$

...

isotropic antenna

Diagram showing the derivation of the directivity formula. It includes a double integral over θ and ϕ from 0 to π and 0 to 2π , respectively, multiplied by $\sin \theta d\phi d\theta$. A question mark is placed above the integral, and a red box highlights the term $4\pi / \Omega_A$.

For arrays such as the Hanson-Woodyard arrays, there is an additional renormalisation factor that accounts for the excess phase delay, δ ,

$$D_{\text{General}} = \frac{\left| \frac{\sin(N\delta/2)}{N \sin \delta/2} \right|^2}{\frac{1}{N} + \frac{1}{N^2} \sum_{m=1}^{N-1} \frac{N-m}{mkd} 2 \cos m\alpha \sin mkd} \quad (3)$$

...

isotropic antenna

In general, the directivity from (3) can be visualised as:

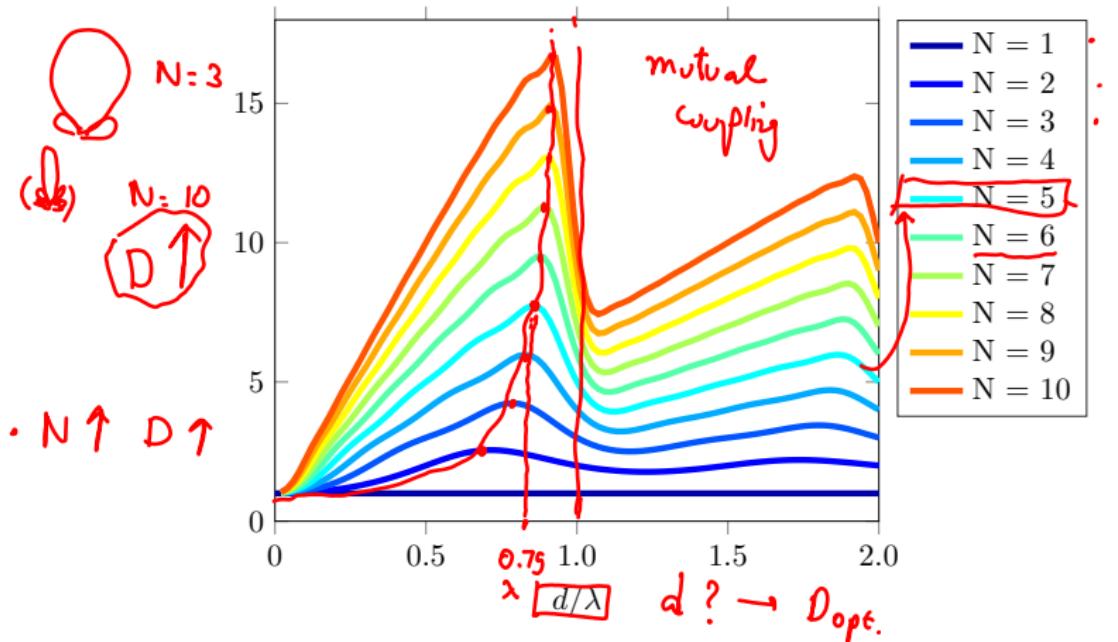
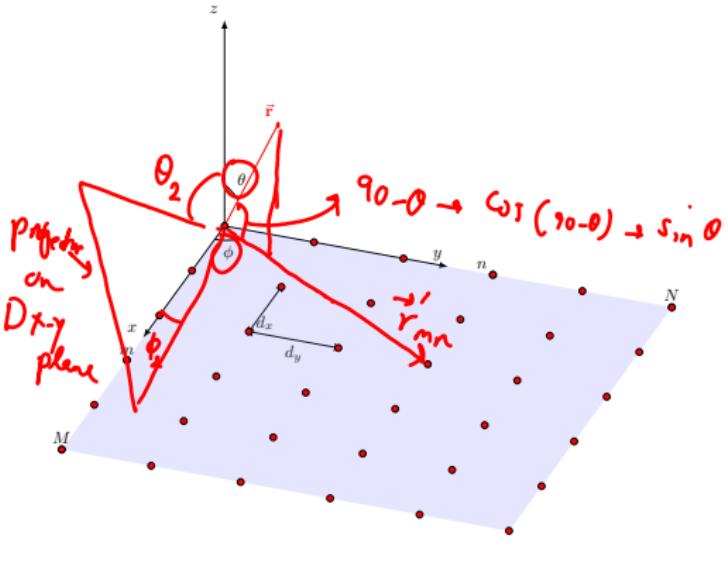


Figure 2: Seeing the directivity as a function of element spacing d and number of elements N .

MULTIDIMENSIONAL ARRAYS

- So far, the 1D arrays we have looked at only yield beamscanning along one angle θ .
- Using multidimensional arrays, we can:
 - Obtain pencil beams
 - Higher directivity and gain
 - Manoeuvre beams in both elevation and $\rightarrow \theta$ azimuthal planes. $\rightarrow \phi$
 - We can have elliptical or rectangular shapes in the 2D case

Figure 3: A 2D rectangular array.

Generally, the Array Factor for an 3D array can be described by first expressing the elements in the form of a position vector:

$$\left\{ \begin{array}{l} \hat{\mathbf{r}}_{mn} = \hat{\mathbf{x}} d_{mn} + \hat{\mathbf{y}} y'_{mn} + \hat{\mathbf{z}} z'_{mn} \end{array} \right.$$

Then,

$$AF(\theta, \phi) = \sum_{m=1}^M \sum_{n=1}^N I_{mn} \exp\left(j(k \hat{\mathbf{r}} \cdot \hat{\mathbf{r}}'_{mn} + \alpha_{mn})\right)$$

In the normalised form, we can write AF as:

$$AF(\theta, \phi) = \frac{\sin M\psi_x/2}{M \sin \psi_x/2} \frac{\sin N\psi_y/2}{N \sin \psi_y/2}$$

where,

$$\psi_x = k d_x \sin \theta \cos \phi + \alpha_x$$

$$\psi_y = k d_y \sin \theta \sin \phi + \alpha_y$$

EXAMPLE — 5×5 PLANAR ARRAY

Element → order

Considering a 5×5 planar array with element spacings $d_x = d_y = \lambda/2$ and the phases $\alpha_x = \alpha_y = -\pi/(2\sqrt{2})$. The radiation pattern looks like:

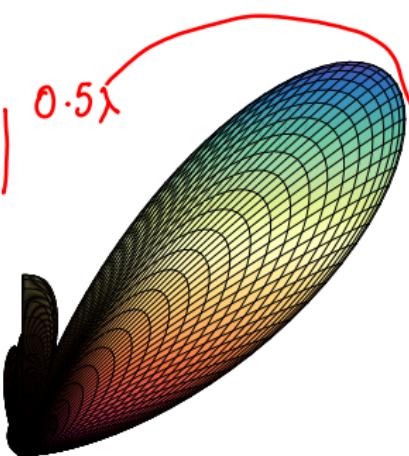
E_x

$$6 \times 6$$

Activity

$$d_x = d_y = 0.76 \lambda$$

$$\alpha_x = \alpha_y = -\frac{\pi}{2}$$



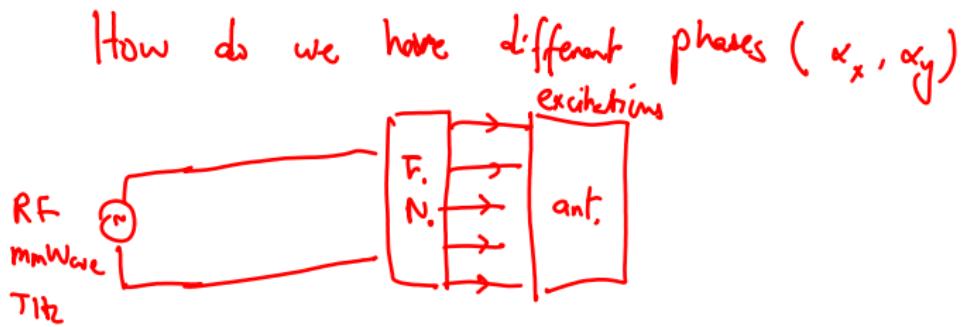
$$kd_x$$

$$\frac{2\pi}{\lambda} \cdot d_x =$$

$$kd_x = \frac{2\pi}{\lambda} \cdot \frac{\lambda}{2} - \pi$$

Figure 4: Radiation Pattern in the Cartesian coordinates.

FEEDING NETWORKS



- The main benefit of phased array antennas is there is no need for mechanical motion.
 - Beam can be steered using electronics
- A disadvantage is each antenna element *must* have a transmission path to the receiver
 - This is done both via hardware and software multiplexing

generates electric signals
feeding network

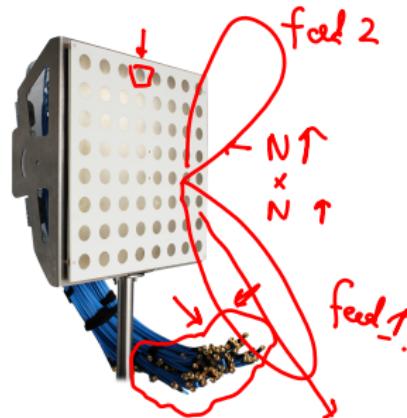


Figure 5: Feeding Cables out of a Massive MIMO Phased Array Antenna

- Most common feeding network
- Also called parallel feed
- We have equal line lengths to each element
 - Phase and amplitude are same across the elements
- Corporate feed can be operated at many frequencies
 - We call it wideband as the operation is independent of frequency

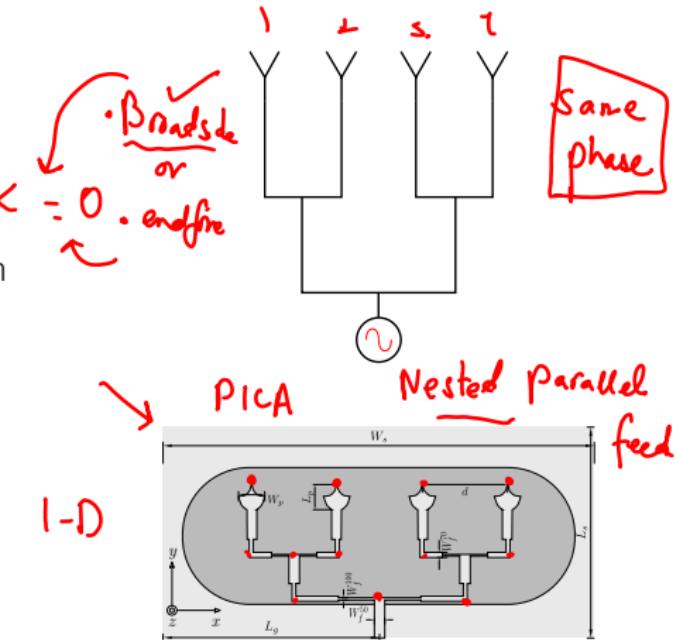
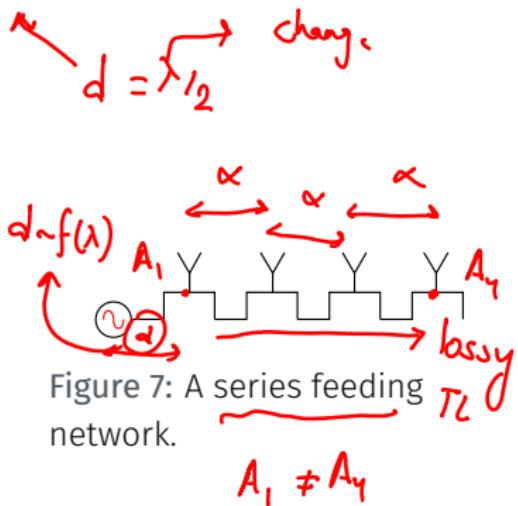


Figure 6: A Planar Inverted Cone Antenna Array ¹. T_{H2} qatkmo

¹Abdoalbaset al Abohmra et al. "An Ultrawideband Microfabricated Gold-based Antenna Array for Terahertz Communication". In: IEEE AWPL (2021). ISSN: 1548-5.

- The Simplest feeding architecture
 - Phase difference can be easily generated
- However, practically loss occurs along the series line
 - This results in unequal amplitudes across the elements
- By changing the frequency, the electrical line length of the feed is changed.
 - Due to this, we have dispersion that limits bandwidth



Narrowband

- Suitable for very large arrays
 - Additional phase shift is introduced commonly through diodes (PIN etc.)
- MEMS based switches can turn a particular arm on or off.
 - Such feeds can withstand high power inputs

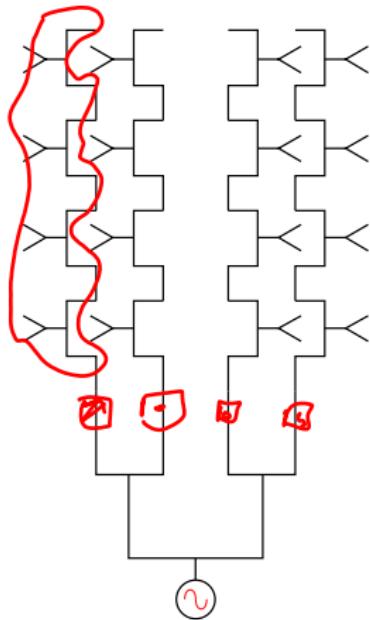


Figure 8: A hybrid corporate-series feeding network.

- For millimetre wave communications, corporate, and series feeding architectures become very complicated
- Other techniques such as *sequentially rotated phase* feeding networks are emerging as attractive candidates
 - Each antenna element is physically rotated
 - Additionally, there is a phase shift to each element
- The advantage over corporate feeding network is that the *resonant response* can be obtained at a higher range of frequencies
- Ensures radiation pattern integrity

d

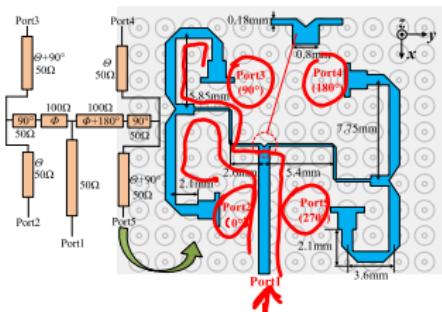


Figure 9: A sequentially rotated phase feeding network¹.

¹Chaojun Ma, Zu-Hui Ma, and Xiupu Zhang. "Millimeter-Wave Circularly Polarized Array Antenna Using Substrate-Integrated Gap Waveguide Sequentially Rotating Phase Feed", In: IEEE AWPL (2019). ISSN: 1548-5757.

SOFTWARE DEFINED RADIO



- A communication system consists of many layers of operations.
- The physical layer is the most important of all.
- Typically, physical layer processing is done via dedicated hardware
- Radio is the technology through which signals are wirelessly transmitted and received
- ✓ Software-defined radio has some or all physical layer functions implemented via software

SOFTWARE DEFINED RADIO

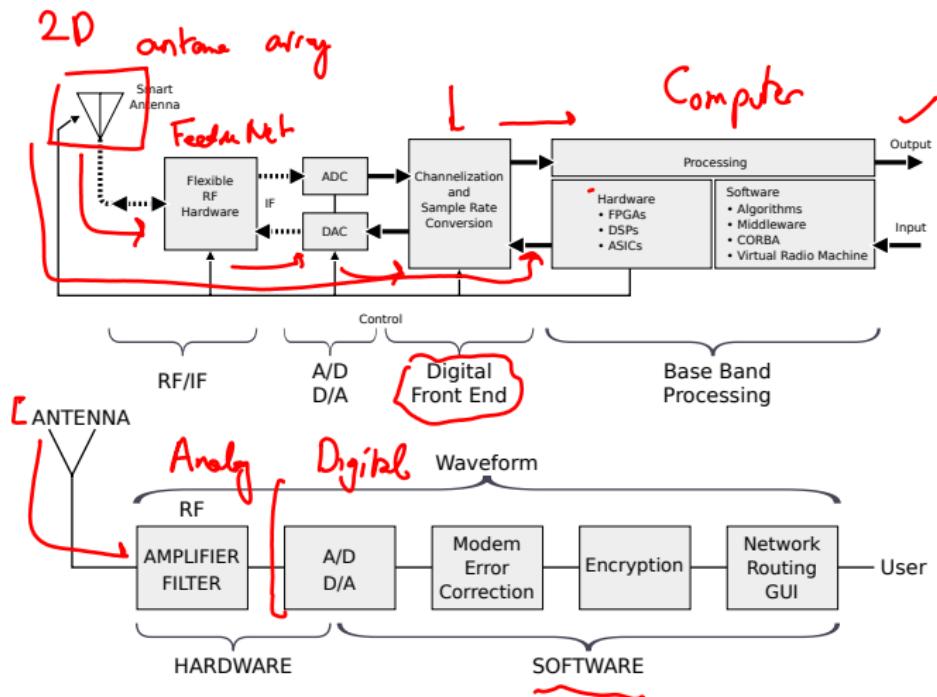


Figure 10: A Typical SDR workflow

- A graphical user interface consisting of flowgraphs through which different signal processing functions such as analog-digital conversion can be performed.
- Some additions let us write **Python** codes within each block
- The software is meant to interface with Universal Software Radio Peripheral (USRP) modules to construct a complete communication system.

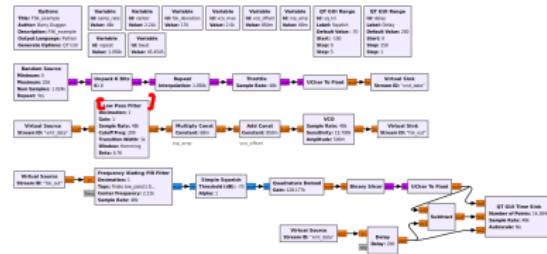


Figure 11: GNU Radio Interface.